

Summary of session A4 at the GRG18 conference: Alternative Theories of Gravity

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Abstract

More than 50 abstracts were submitted to the A4 session on *Alternatives Theories of Gravity* at the GRG18 conference. About 30 of them were scheduled as oral presentations, that we summarize below. We do not intend to give a critical review, but rather pointers to the corresponding papers. The main topics were (i) brane models both from the mathematical and the phenomenological viewpoints; (ii) Einstein-Gauss-Bonnet gravity in higher dimensions or coupled to a scalar field; (iii) modified Newtonian dynamics (MOND); (iv) scalar-tensor and $f(R)$ theories; (v) alternative models involving Lorentz violations, noncommutative spacetimes or Chern-Simons corrections.

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I. EXTRADIMENSIONAL THEORIES

A. Brane models

Many recent papers have discussed about the absence or existence of a ghost degree of freedom in the DGP brane model [1]. K. Izumi presented his work [2] in collaboration with K. Koyama and T. Tanaka, in which the consequences of introducing a second brane are analysed. It allows to avoid the ghost present in the helicity-0 component of the massive spin-2 graviton, but a spin-0 ghost is generated instead, and the authors show how they are related. However, they argue that such a ghost mode may be harmless in de Sitter background, using the fact that the UV cutoff of the effective theory is lower than the Planck scale.

Several presentations were devoted to the Randall-Sundrum brane model [3, 4], and more precisely to the second one (RS-II). It has been conjectured that no brane-localized static black hole exists in this model if its size is larger than the bulk curvature scale [5, 6]. N. Tanahashi, again in collaboration with T. Tanaka [7], checked this conjecture by constructing time-symmetric initial data, assuming axisymmetry around the extra dimension. Such initial data can be constructed for a size of the apparent horizon much larger than the bulk curvature scale, but the horizon area is always smaller than that of the black string of the same mass, consistently with the conjecture. The authors also successfully checked their construction by applying it to the case of a 4-dimensional bulk spacetime, in which a static brane-localized black hole solution is known analytically [8].

A. Majumdar clearly summarized his works on black holes in extradimensional theories, and notably in the RS-II model [9, 10, 11, 12, 13]. Primordial black holes survive longer in this model (contributing thus to dark matter), and the author shows that more black-hole binaries are formed (providing sources of gravitational waves). Gravitational lensing also differs from the Schwarzschild case, although it is not yet possible to test these theories with present experimental accuracy.

L. Gergely gave a very nice talk about his work [14] in collaboration with Z. Keresztes and G. Szabó, in which the cosmological predictions of the RS-II model are confronted with available supernova data. The authors derive difficult analytical results, and show that experimental data can be perfectly fitted within this scenario. However, they insist on the fact that alternative models are not ruled out either.

Four talks [15, 16, 17, 18] were given by students and collaborators of Z. Stuchlík, who probably holds the record number of independent abstracts submitted to the GRG18 conference. There were devoted to various observable effects of brany black holes, which involve a tidal charge (similar to the square electric charge Q^2 of the standard Reissner-Nordström solution, but here with any sign). M. Kološ [15] focused on circular geodesics around such black holes, and underlined the quantitative differences with the Reissner-Nordström case. J. Schee [16] studied null geodesics around a rotating brany black hole, i.e., Kerr-Newman geometry with any sign for the tidal charge. He clearly classified such geodesics in 7 different regions, and exhibited the small predicted effects on the black hole images. A. Kotrlová [17] analysed the effect of the tidal charge on the quasiperiodic oscillations (QPOs) observed in rotating black holes, and discussed in which situations the spin and the tidal charge can be determined from observation. She pointed out however that some systems involving more than one resonant point cannot be explained even within this brane framework. J. Hladík [18] focused on trapped null geodesics around compact stars, whose exterior spacetime corre-

sponds again to the above brany black holes. He studied neutrino trapping in this braneworld as compared to the general relativistic case [19], and showed that it can be efficient under some precise conditions (but the experimental accuracy needed to discriminate the theories was not computed).

As opposed to the above phenomenological studies, the work presented by J. E. Rojas-Marcial [20] was quite mathematical. He considered Born-Infeld-type theories, in which the determinant defining the action involves either gauge fields (as usual) or extrinsic curvature terms related to a brane. The authors constructed the conserved stress tensor and derived the general field equations. Because of the presence of higher derivatives, the stability of such models is however unclear.

B. Gauss-Bonnet

Adding the Gauss-Bonnet topological invariant $R^2_{\mu\nu\rho\sigma} - 4R^2_{\mu\nu} + R^2$ to the Einstein-Hilbert Lagrangian is well known not to contribute to the field equations in 4 dimensions, but it does in higher dimensions or if it is multiplied by a nonconstant field.

N. Dadhich and K. Maeda found in [21, 22] a static black hole solution in more than 4 dimensions, when both the Gauss-Bonnet term and a cosmological constant are present (and their coefficients related). N. Dadhich presented the recent extension and interpretation of this solution proposed by the authors [23]. Pure gravity in 6 dimensions can be seen in 4 dimensions as the collapse of charged null dust forming a black hole. The authors' conclusion is that matter (the black hole) is produced by gravity in this case. The audience pointed out that this is not the first example, since dimensional reduction does generate gauge and scalar fields from a pure extradimensional metric, and since ingoing gravitational waves can form a black hole even in 4 dimensions. But the exact solution [21, 22] remains nice and interesting anyway.

J. Oliva presented his work [24, 25] in collaboration with G. Dotti and R. Troncoso, in which a static wormhole solution is constructed in 5-dimensional Einstein-Gauss-Bonnet gravity with a cosmological constant. The authors provide a physical interpretation, analyse the causal structure, and above all prove that the solution is stable against scalar field perturbations (no symmetry being assumed for such perturbations).

I. Neupane, in collaboration B. Leith [26], considered the Gauss-Bonnet term in 4 dimensions but multiplied by a function of a scalar field. He showed that the dark energy responsible for the accelerated expansion of the Universe can admit an equation of state $p/\rho \equiv w < -1$ in this framework, but that it tends to -1 when $t \rightarrow \infty$. Contrary to other models with $w < -1$, the present one is stable at least at quadratic order (since the scalar-Gauss-Bonnet term is perturbatively of cubic order), and it admits nonsingular solutions for a wide range of the scalar-Gauss-Bonnet coupling constant.

II. MODIFIED NEWTONIAN DYNAMICS

In order to explain the flat rotation curves of galaxies and clusters, one may invoke either the existence of dark matter or a MODification of Newtonian Dynamics at large distances (MOND), as M. Milgrom proposed in 1983 [27]. Instead of its Newtonian expression $a_N = GM/r^2$, the acceleration of a test particle is assumed to read $a = \sqrt{a_N a_0}$ when a is smaller

than a universal constant a_0 . This simple recipe superbly accounts for galaxy rotation curves.

However, cluster rotation curves still need a significant amount of dark matter even within this MOND framework. It has been argued that neutrinos could form this dark matter, since they can cluster at such scales (whereas they are too light to cluster at the scale of a galaxy). R. Takahashi presented his work in collaboration with T. Chiba [28]. They studied weak lensing in three clusters, and proved that the neutrino mass should be larger than 2 eV to explain the data (and even ~ 8 eV for one cluster). This is thus inconsistent with the particle physics limit, and the authors' conclusion is that dark matter around galaxy clusters must involve something else than neutrinos.

The success of MOND for galaxy rotation curves remains anyway impressive, and many physicists have thus looked for field theories reproducing its behaviour as naturally as possible. One of the best proposals is the Tensor-Vector-Scalar (TeVeS) model constructed by J. Bekenstein [29]. The physical metric to which matter is assumed to be universally coupled takes however the rather complicated form $\tilde{g}_{\mu\nu} \equiv e^{-2\varphi} g_{\mu\nu}^* - 2U_\mu U_\nu \sinh(2\varphi)$, where $g_{\mu\nu}^*$ is the Einstein (spin-2) metric, U_μ is a unit norm vector field, and φ is a scalar field. M. Sakellariadou presented her work [30] in collaboration with M. Mavromatos, in which such fields and such a physical metric are shown to appear naturally in string theory. The unit vector field comes from the average recoil 4-velocity of D0-branes (point particles) interacting with neutrino string matter. Moreover, neutrinos not only contribute to the dark matter density within this scenario, but also to the dark energy density. Such an increased value of Ω_Λ is precisely needed in TeVeS to reproduce the CMB spectrum.

G. Esposito-Farèse presented his work in collaboration with J.-P. Bruneton [31], in which the stability and the mathematical consistency of various MOND-like field theories is analysed, including TeVeS and new models proposed by the authors. Their conclusion is that no present theory passes all experimental tests while being stable and admitting a well-posed Cauchy problem, besides the unnatural fine tuning needed to construct them. On the other hand, it is possible to account for the Pioneer anomaly (if confirmed) within a stable and consistent model, but it is fine-tuned too.

Although the aim of MOND was *a priori* to avoid the dark matter hypothesis, L. Blanchet proposed an original reinterpretation [32, 33]: Its phenomenology may be caused by some special kind of dark matter filling the Universe. Assuming that it is formed by gravitational dipoles, he shows that their polarization aligns with the gravitational field of ordinary matter. Their own gravitational field thereby modifies the Newtonian one. By choosing an appropriate force law between the gravitational charges constituting each dipole, the author shows that the MOND law $a = \sqrt{a_N a_0}$ can be recovered naturally for small accelerations. The classical version of this model needs to assume the existence of negative gravitational charges, but the author has also devised a relativistic version avoiding them.

M. Seifert presented his study [34], based on his previous work [35] in collaboration with R. Wald. He devised a general method to analyse the stability of static, spherically symmetric solutions in any diffeomorphism covariant field theory: He considers spherically symmetric perturbations and computes the eigenvalues of the oscillation frequencies. He then applied this method to various alternative theories of gravity, and notably confirmed that the above TeVeS model is unstable. Indeed, the Sun would not last longer than 2 weeks within this theory. Since he also applied his method to $f(R)$ and scalar-tensor theories, this provides a natural transition with the next Section.

III. SCALAR-TENSOR THEORIES

A. Brans-Dicke-like models

Numerical simulations of structure formation are remarkably successful when assuming the existence of pressureless cold dark matter, but they generically predict cuspy density profiles at the center of galaxies. J. Cervantes-Cota presented his recent study [36] in collaboration with M. Rodríguez-Meza and D. Nuñez, in which a scalar-tensor theory is invoked to avoid such cuspy profiles. Besides the presence of dark matter, this model involves two free parameters (the mass of the scalar field and its coupling constant to matter), that the authors constrain by fitting both rotation curves and luminosity profiles. They show that some parameters correspond to shallow density profiles in galaxy centers. However, the authors do not discuss whether post-Newtonian tests are passed in the solar system and binary pulsars. This may be the case if the scalar field is only coupled to dark matter but not to baryonic matter. On the other hand, the baryonic matter-scalar coupling constant they need in Ref. [37], for instance, is much too large to satisfy such post-Newtonian constraints.

Scalar-tensor theories can be written in terms of different variables. The most popular ones are (i) the Einstein frame, in which the kinetic term of the metric is the standard Einstein-Hilbert (spin-2) action, but where the matter action involves an explicit dependence on the scalar field; (ii) the Jordan frame, in which the metric is minimally coupled to matter, but where the spin-2 and spin-0 kinetic terms are not diagonalized. The simplest way to prove that the Cauchy problem is well posed for such theories is to analyse it in the Einstein-frame, since they reduce then to general relativity, the scalar field playing the role of an extra matter field. The work [38] that M. Salgado presented analyses this Cauchy problem in the Jordan frame instead. This is much more complicated than in the Einstein frame, and the author needs to introduce a new class of harmonic slicings to evolve the lapse function in the $3 + 1$ ADM decomposition. This allows him to confirm that the Cauchy problem is indeed well posed. Since the change of variables from one frame to the other can be singular in particular situations, the audience was surprised that this analysis in the Jordan frame did not impose constraints on the derivatives of the scalar field.

Theories whose Lagrangian involves a function of the scalar curvature, $f(R)$, are well-known to be equivalent to scalar-tensor theories. The R^n models studied by J. Leach, in collaboration with N. Goheer and P. Dunsby [39], are thus of this kind. In the same spirit as their previous paper [40], they have performed a detailed analysis of the cosmological dynamics of such models, for anisotropic homogeneous Bianchi universes. They notably find the nature of equilibrium points, and investigate static solutions and possible bouncing behaviours.

B. $f(R)$ theories in the Palatini formalism

The above equivalence of $f(R)$ theories with scalar-tensor theories assumed that the scalar curvature was a function of the metric tensor and its first derivatives. There is a subtle but crucial difference when considering such theories in the first order (Palatini) formalism, in which the metric $g_{\mu\nu}$ and the connection $\Gamma_{\mu\nu}^\lambda$ are treated as independent fields. As shown notably in [41, 42], $f(R)$ theories are still equivalent to scalar-tensor theories, but the scalar field does not propagate: It does not have any kinetic term in the Einstein frame. It behaves thus as a Lagrange parameter, and its field equation imposes a constraint.

More precisely, its value can be written in terms of the matter fields, and its presence in the matter field equations yields thus new unexpected matter-matter interactions. É. Flanagan showed in 2003 [41, 42] that specific models are ruled out by particle physics data, and that this difficulty is *a priori* generic for $f(R)$ theories in the Palatini formalism. [Note however that in these references, the matter action was assumed to depend on the metric and its derivatives, but not on the independent connection $\Gamma_{\mu\nu}^\lambda$; if the first-order formalism is extended to the matter action itself, the analysis is more involved and the conclusion may be less dangerous for this class of models.]

E. Barausse presented his work [43], in collaboration with T. Sotiriou and J. Miller, in which another serious difficulty of Palatini $f(R)$ theories is pointed out. They consider polytropic spheres in this framework, and show that the field equations are singular at their surfaces (because terms coming from radial derivatives of the function f' behave as derivatives of the matter density). For a polytropic index $\frac{3}{2} < \Gamma < 2$, they prove that there is a curvature singularity at the surface of the body. Their work was criticized in [44], where it is argued that a single polytrope does not describe realistic stars up to their surface. However, E. Barausse underlined that even if one considered a smooth crust at the surface, this class of theories would anyway predict huge tidal effects. Large tidal forces would notably occur in the outer regions of a dilute gas of solar-system size, and this seems unrealistic.

Independently of the above difficulties, R. Tavakol analysed in depth the cosmological dynamics of such Palatini $f(R)$ theories, in collaboration with S. Fay and S. Tsujikawa [45]. His presentation was particularly pedagogical, and his main conclusion was that such theories can predict 3 out of the 4 required cosmological phases (early inflation, radiation domination, matter domination, late de Sitter expansion). This is thus better than $f(R)$ theories in the (second order) metric formalism. However, it seems impossible to predict inflation *followed* by a radiation-dominated era in the present Palatini framework.

Still in this framework, K. Uddin presented his study of cosmological perturbations [46], in collaboration with J. Lidsey and R. Tavakol. He compared two different approaches developed in the literature: direct linearization of the field equations, and an application of Birkhoff's theorem. It happens that the latter (simpler) method does not yield pressure gradients in the perturbation equations, contrary to the latter (more rigorous) one. The authors determine for which theories and under which conditions the simpler method anyway gives reasonable results.

IV. ALTERNATIVE MODELS

Although Lorentz symmetry is very well tested experimentally, it may happen that it is violated at the Planck scale, where quantum gravity effects cannot be neglected. R. Bluhm presented his work [47], in collaboration with A. Kostelecky, in which they study gravitational effects occurring when Lorentz symmetry is spontaneously broken. He notably underlined that this also causes a breaking of diffeomorphism invariance, and the generation of both massless (Nambu-Goldstone) and massive modes. The related observable effects are described in terms of an effective field theory.

A. Kobakhidze summarized his works with X. Calmet [48, 49], in which they formulate a theory of gravitation on a noncommutative spacetime. They exhibit different implementations of general coordinate invariance and local Lorentz invariance, focusing on unimodular gravity (volume-preserving diffeomorphisms). They construct twisted gauge symmetries in

the spirit of J. Wess *et al.* [50, 51], and show how a fully covariant theory of gravity may be defined on Riemann-Fedosov manifolds.

Chern-Simons modified gravity was first constructed by S. Deser *et al.* in 2+1 dimensions [52], and it has been extended to 3+1 dimensions by R. Jackiw and S. Pi [53]. In this theory, the Schwarzschild solution holds but not the Kerr one. In 2+1 dimensions, the latter is replaced by the rotating black hole solution of Ref. [54], in which frame dragging is enhanced. K. Konno presented his work [55] in collaboration with T. Matsuyama and S. Tanda, in which they look for rotating black holes in 3+1-dimensional Chern-Simons modified gravity. They do not find an exact solution, but analyse perturbations of the Schwarzschild one. The theory depends on a fixed vector field ν_μ , called the embedding coordinate. When it is timelike, the authors show that no finite-mass rotating black hole exists in this theory (at least at the perturbative level). On the other hand, when ν_μ is spacelike, rotating black holes exist for any mass, and the authors exhibit the form of the solution.

V. CONCLUDING REMARKS

The main puzzles of theoretical and experimental gravity trigger our interest for alternative theories. Quantum gravity suggests possible Lorentz violations, noncommutative spacetimes, or extradimensional theories. The latter imply the existence of scalar partners to the graviton, and even more subtle phenomenological effects occur if our 4-dimensional spacetime is a brane embedded in the higher-dimensional bulk. On the other hand, the experimental evidence for 72 % of dark energy and 24 % of dark matter in our Universe may be a hint that general relativity fails at large scales. All the works presented in this session addressed at least one of these questions. Some no-go theorems or negative results usefully reduce the space of allowed models to be explored, while new ideas recall us that Nature might be richer than we expect. Let us bet that the quest for alternative theories of gravity will not end until an elegant and consistent model predicts all experimental data.

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